# AN IMPROVED METHOD OF BACK AZIMUTH DETERMINATION WITH A MULTI-ARM OFIS

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## ABSTRACT

The detection of infrasound in the presence of wind is challenging. Increasing wind speeds lead to higher noise floors. While the exact nature of the noise is still a subject of investigation, several technologies and array configurations have been developed to maximize the signal to noise ratio and lower the detection threshold. Optical fiber infrasound sensors (OFIS) are long compliant tubes wrapped with two optical fibers that integrate pressure change along the length of the tube with laser interferometery. Spatially incoherent wind noise is naturally attenuated relative to spatially coherent infrasound. Because the signal pressure variation is integrated along the length of the tube, the instrument response is a function of the orientation of the OFIS arms relative to the orientation of the wavefront. We show with theory and real infrasound data recorded at Piñon Flat Observatory in southern California that this spectral property can be exploited with multiple OFIS arms in different ways to determine the phase velocity of infrasound signals. Based on these findings and unpublished results, we propose two OFIS configurations as alternatives to rosette pipe array infrasound stations.

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## OBJECTIVES

Infrasound is generated by a variety of natural and manmade sources, and can travel far distances under certain atmospheric conditions. Atmospheric explosions are particularly good at producing far-reaching infrasound in the 0.01-10 Hz band (Landau and Lifshitz, 1959). This has recently led to increased interest in infrasound for Comprehensive Nuclear Test-Ban Treaty (CTBT) compliance verification. The tool for this monitoring is the International Monitoring System (IMS), which is to include 60 globally distributed infrasound stations, about 20 of which are currently constructed.

Recording signals of interest is a challenge in the presence of wind. Increasing wind speeds correlate with increasing noise levels across the entire infrasound band (Kaimal and Finnigan, 1994). One source of wind-related noise is the advection of density anomalies across the sensor at the wind speed (<20 m/s; Taylor's hypothesis). Because infrasound travels at much faster acoustic speeds (~330-350 m/s) and propagates across the Earth's surface at subhorizontal angles (e.g., McKisic, 1997), large-aperture arrays of sensors and associated processing techniques are typically used to separate the rapidly moving signal from the more slowly moving turbulence, and determine the direction to the source.

Spatial wind filters also help reduce turbulence noise before it reaches the sensor. There are generally two types of spatial filters: pipe networks and hose networks. Pipe networks are often buried and centrally connected to a microbarometer or microphone. A common design is the "rosette" pipe filter, consisting of several clusters or rosettes of low-impedance pipe network inputs (Alcoverro, 1998; Hedlin and Raspet, 2003). These rosettes vary in aperture from 18 to 70 m depending on the frequency band of interest. Hedlin et al. (2003) and Hedlin and Alvocerro (2005) evaluated an array or "rosette" of underground pipes centrally connected to a microbarometer or microphone sensor. As the spatially coherent infrasound wavefront propagates across the ports of these wind filters, the signal diffuses into the pipe, and propagates toward the central sensor at the speed of sound where they constructively interfere. If wind noise originates from density anomalies that are advected across the array (Taylor hypothesis) with a spatial coherence that is shorter than the rosette aperture, the noise destructively interferes at the central sensor. This leads to a standard amplitude signal to noise gain of $n^{1/2}$, where $n$ is the square root of the number of pipe array ports. The rosette response depends on the apparent speed and frequency of the signal that propagates across the array as well as the array size, in part because the signals travel through the pipe network to the sensor at the speed of sound. The disadvantages of rosette filters are that they are usually large and logistically challenging to build, the rosettes can strongly attenuate signal strength depending on their aperture, significant resonance occurs for frequencies about ~0.7 Hz, and the arrays are not suited for temporary deployments. However, this filter is fairly successful in attenuating wind noise, and is employed by many of the IMS infrasound arrays in arrays of up to 8 elements and apertures of up to 2 km across.

Another type of wind filter is a porous hose network. These porous hoses are inexpensive, and connect to a central microphone or microbarometer in a similar fashion as in the pipe arrays. However, the infrasound diffuses into the porous hose at all points of contact with the wavefront. This provides more points of sampling for the coherent wavefront, which could increase the signal to noise ratio more than that for a rosette pipe array. Although the arrays are relatively simple to deploy, the porous hoses kink easily and are not easy to manipulate. It is also not uncommon to have a high noise level that disappears when the hose is replaced or disconnected from the sensor.

A more recent technique is to create a massive array of inexpensive piezo-electric microphones, and to use array processing techniques to attenuate incoherent wind noise while preserving coherent signal. The success of this technique depends on the sensitivity of the microphones, the aperture of the array, and the number and spacing of the sensors used to form the beam. The disadvantage of this technique is that it can require extensive computational and data-storage resources. Shields (2005) used an array of 28 sensors that had ~0.02 V/Pa sensitivity to investigate the optimum sensor separation distance. He shows that wind turbulence has a consistent spatial coherence for wind speeds in the 4–7 m/s range, allowing one to select the optimum sensors in the array to use in the beam for a known wind speed and direction to achieve better than $n^{1/2}$ noise reduction (where $n < 28$).

### Motivation for this Study

The optical fiber infrasound sensor is described by Zumberge et al. (2003) as a different approach to reducing wind noise. The OFIS is a long compliant tube that measures instantaneous pressure variation along the length of the tube with an effective sensitivity (for comparison purposes) of ~60-180 V/Pa depending on the OFIS length of 30-90 m

and the size and geometry of the interferometer ellipse. These tubes can be oriented in a circle or a line. A circle does not maximize the distance over which an OFIS can spatially average incoherent noise. Zumberge et al. (2003) and recent unpublished work shows that the noise floor of a 90-m linear OFIS is as much as 20 dB lower than that of a traditional 70-m rosette pipe filter for winds up to 3 m/s in the 1–10 Hz band. While the linear OFIS is efficient in attenuating wind noise, its feasibility as an operational solution to infrasound data collection also depends on the ability to use it to record the infrasound signal reliably and measure the signal propagation direction (back azimuth and elevation angle). In this paper, we demonstrate three fundamental techniques and their variations on how one can use an array of linear OFIS arms to determine the phase velocity direction. The theory is presented, along with applications to real data, and conclusions regarding the optimum array configuration.

## RESEARCH ACCOMPLISHED

### Sensor Directivity

The velocity vector of the propagating wavefront in free space is hereinafter referred to as the "phase velocity" *c*. Similarly, we refer to the "apparent velocity" as the velocity of the intersection of the wavefront with the Earth's surface. The instrument response, *R*, of a linear OFIS relative to a reference point at the end of the OFIS has the amplitude and phase response

$$R_a(f) = \mathrm{sinc}\left(\frac{L\pi f}{c}\cos(\theta)\right) \tag{1}$$

$$R_p(f) = L\pi f\cos(\theta)/c \tag{2}$$

where *f* is frequency, *L* is the length of the OFIS, and $\theta$ is the angle between the phase velocity direction and the OFIS

$$\theta = \cos^{-1}(\cos(\theta_H)\cos(\theta_V)) \tag{3}$$

where $\theta_H$ are $\theta_V$ are the horizontal and vertical and angles, respectively (Zumberge et al., 2003). The phase response is just a time shift from the center of the OFIS to reference point. For typical infrasound signals from distance sources, is $\theta_V$ = 0-30° (subhorizontal) and $\theta \cong \theta_H$. Figure 1a shows $R_a$ as a function of $\theta$ for three typical infrasound signal frequencies. Figure 1b shows the variation of $R_a$ with frequency for several angles. For low frequencies and long wavelengths (or orthogonal angles), the OFIS is effectively a point sensor and records the wavefront perfectly. For all other conditions, a frequency-dependent attenuated version of the signal is recorded. In other words, the fingerprint of the directionally-dependent instrument response is recorded in the amplitude spectrum of the signal.

The sinc form of this response can also be thought of as the Fourier transform of a boxcar time series function, which represents the averaging of an impulse function signal as it propagates across the OFIS. For rays perpendicular to the OFIS, the impulse signal is recorded perfectly (flat amplitude spectrum) since the wavefront is parallel to the OFIS. For rays at oblique angles to the OFIS, the impulse is smeared in time into a boxcar shape with lower amplitude, resulting in the narrower sinc function for the amplitude spectrum.

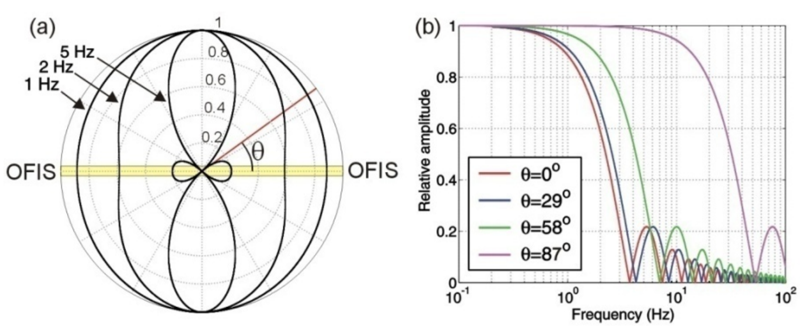



**Fig. 1. Frequency response *R* for a 90-m long OFIS as a function of frequency and angle θ from the length of the OFIS (eqns. 1,3).**

In the frequency domain, each recorded OFIS signal $S_r$ is a convolution of the signal waveform with the instrument response $S_r = S_w R$. Conversely, if $\theta$ is known, one can deconvolve the instrument response to determine the signal spectrum $S_w = S_r / R$. Although the forward step is a stable, the inverse step is not in this case because the denominator $R$ has near-zeros for certain frequencies (Fig. 1). To get around this problem, we use water-level deconvolution (e.g., Langston, 1979), which increases the amplitude of $R$ in these troughs to 2% of the maximum.

**Phase Velocity Determination Techniques**

In this section, we describe the theory behind the different techniques used to derive the phase velocity direction. Most of these techniques are a type of directional instrument-response dependent beamforming. Figure 2 shows different OFIS configurations (a-d) that are appropriate to use with these techniques if the length of the OFIS arms are longer than 1/4 wavelength of the signal. Configuration (e) could be used in the same sense as pipe rosette filters or hose arrays with no azimuthal directionality.

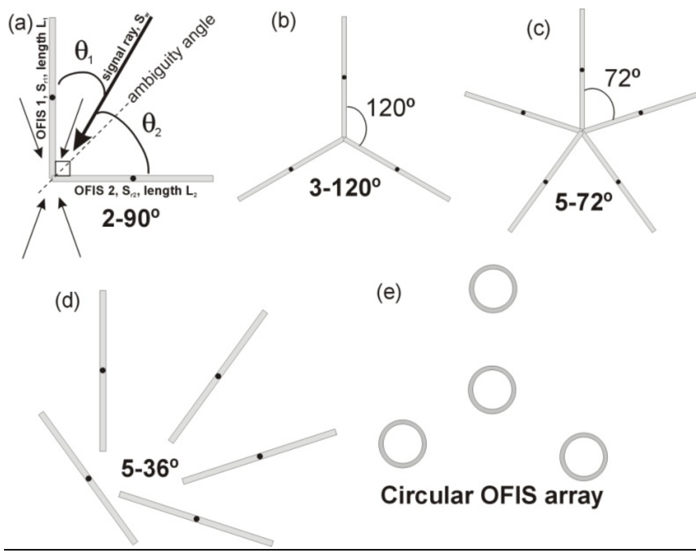



**Fig. 2. Some possible OFIS array configurations.**

**Water-Level Deconvolution (WLD), Predicted OFIS Comparison Technique**

One usually wants to obtain $\theta$ and the signal with the highest signal to noise ratio (SNR) possible. One approach is to have an array of several circular OFIS in a configuration with an aperture optimized for beamforming in the frequency band of interest. However, one can exploit the directionality property of a linear OFIS by forming an array of OFIS arms in different orientations. For each possible ray orientation, an $R(\theta)$ exists that relates $S_w$ to what should be recorded by each OFIS. Because the recorded OFIS signal is $S_r = f(S_w, \theta, L, c)$, where only $S_w$ and $\theta$ are the unknowns, one can estimate $S_w$ and $\theta$ if one records the signal on two OFIS with different orientations $S_{r1} = f(S_w, \theta_1, L_1, c)$ and $S_{r2} = f(S_w, \theta_2, L_2, c)$, where $\theta_1$ and $\theta_2$ are related to the phase velocity direction by the array configuration (Fig. 2a). One can do this by substitution, i.e., using $S_{r1}$ to predict $S_w{}^p$, and then $S_{r2}{}^p = S_w{}^p R_2 = S_{r1} R_2 / R_1$, and perform a grid search over trial $\theta$ to minimize the sum of squares of the misfit between the inverse Fourier transforms of $S_{r2}$ and $S_{r2}{}^p$. The global minimum corresponds with the phase velocity direction. Knowledge of the misfit function allows us to calculate formal 2σ error bars by assuming the misfit function reflects a random chi-squared noise process (Jenkins and Watts, 1968). We determine the number of degrees of freedom based on the average recorded signal bandwidth (Silver and Chan, 1991), which frees us from the requirement that the observed signal samples are independent of each other (white spectrum).

The accuracy using this technique (which we call "WLD" even though that is technically the abbreviation for a type of deconvolution) is mostly dependent on the SNR and the orientation of the ray with respect to the OFIS arms that are being used to estimate the waveform signal (deconvolution step). For example, in Figure 2a the deconvolution of $R(\theta_1)$ from OFIS 1 (using OFIS 1 to predict OFIS 2) is more prone to noise amplification in the regional around the global minimum than the deconvolution of $R(\theta_2)$ from OFIS 2 (using OFIS 2 to predict OFIS 1) for the shown ray. There are three ways to compensate for this sensitivity. First, one can sum both misfit functions throughout the grid search. Another approach is to skip grid points for which the trial ray is within some angle of the reference OFIS orientations (this only works if you have an array of more than 2 OFIS arms). Finally, one can use only the OFIS arm that is most perpendicular to the trial ray as the reference OFIS.

The 2-90º OFIS configuration has a special property (Fig. 2a). The 90º separation offers identical spectral resolution for phase velocity directions in all of the quadrants. In addition, it is computationally the fastest in part because one only needs to do the grid search within one of those quadrants to get the spectral resolution for all possible phase velocity directions. For each trial, we can therefore obtain the spectral constrains, and then time shift the resulting inverse Fourier transformed waveform by $dt = (L_2 \cos\theta_{H2} - L_1 \cos\theta_{H1})\cos\theta_V / 2c$ to calculate four separate quadrant misfit values (if we set $R_p$=0). The 2-90º configuration has been tested by analyzing recorded signals at the Piñon Flat Observatory with the WLD method (unpublished data). The configuration works fairly well for sub-horizontally propagating signals with a very good to excellent SNR (> 12 dB). However, it does not work well for signals with a low SNR. In addition, a fundamental limitation of any two-arm OFIS configuration is that it cannot be used to determine a phase velocity direction within the vertical plane defined by the azimuth in between the two OFIS (Fig. 2a). Only higher order OFIS configurations can resolve that ambiguity.

In general, the WLD technique can be applied to multiple OFIS arms in different configurations, but the computational time for the above method is proportional to $n(n-1)$ and there is an additional doubling of CPU time associated with going from a 2-90º configuration to a higher order configuration because quadrant symmetry is replaced by hemisphere symmetry.

**Simultaneous Array Deconvolution (SAD) Technique**

The WLD technique can amplify noise because of the deconvolution step. The simultaneous array deconvolution (SAD) is a more stable deconvolution technique. One estimates the unattenuated signal spectrum by weighting, as a function of frequency and trial phase velocity direction, the recorded spectra of the OFIS arms such that only those OFIS arms that are in a good position to estimate $S_w$ at each frequency are effectively used in the deconvolution. For example, if OFIS 1, 2, 3, and 4 recorded a signal with a phase velocity direction that was 0º, 29º, 58º, and 87º from those OFIS arms, respectively (Fig. 1b), SAD would determine for a frequency of 7 Hz the signal spectrum from the OFIS spectra weighted from greatest to least: OFIS 4, 2, 1, and 3. In other words, the SAD technique is theoretically more stable than the water-level deconvolution approach because recorded spectra values, where troughs are predicted to exist by *R*, are effectively not used to estimate the signal spectrum. This approach is a least-squares inversion. Assume $\boldsymbol{D}$ is an *m* x *n* matrix containing the OFIS recorded complex spectra, where *m* is the number of OFIS and *n* is the length of the spectrum. The forward problem is represented in matrix notation as $\boldsymbol{D} = \boldsymbol{GW}$, where $\boldsymbol{W} = \boldsymbol{wI}$ contains $S_w$ and $\boldsymbol{G}$ is an *m* x *n* matrix containing the *m* response functions of length *n* for the trial phase velocity direction. The least squares solution for $\boldsymbol{D}$ given $\boldsymbol{W}$ is $\boldsymbol{W} = [\boldsymbol{G}^T\boldsymbol{G}]^{-1}\boldsymbol{G}^T\boldsymbol{D}$. Expanding for the $i^{th}$ frequency component,

$$w_i = \frac{G_{1i}D_{1i} + G_{2i}D_{2i} + \cdots + G_{mi}D_{mi}}{G_{1i}^2 + G_{2i}^2 + \cdots + G_{mi}^2}$$

This equation represents the best technique for estimating $S_w$ providing that each OFIS has the same intrinsic noise level. From here, one can calculated the predicted OFIS recordings in the same manner as discussed above, and derive a misfit function. Alternatively, another measure of the misfit is the residual function in frequency space. For the trial phase velocity direction $\theta_t$

$$M(\theta_t) = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(D_{ij} - G_{ij}w_j\right)^2$$

The advantage to using the time-domain misfit is that you can normalize each waveform before taking the misfit, which allows for compensation of calibration problems and can sometimes improve stability.

**Array Response Comparison (ARC) Technique**

The array response comparison (ARC) technique does not involve deconvolution. Recall that the observed signals for 2 OFIS are $S_{r1} = S_w R_1$ and $S_{r2} = S_w R_2$. One can multiply both sides of these equations by the opposite instrument response function $S_{r1} R_2 = S_w R_1 R_2$ and $S_{r2} R_1 = S_w R_2 R_1$. Because of the commutative property of multiplication in the frequency domain, the right hand side of these two equations are equal, and therefore $S_{r1} R_2 = S_{r2} R_1$. Each of these products can be thought of as the array response to the signal if the centers of the OFIS were collocated and the OFIS arms optically interconnected. Each OFIS can be used to estimate the array response for some trial phase velocity direction. For the correct direction, the array responses should be identical. Therefore, for *n* OFIS arms, one can perform the grid search within a hemisphere, where for each trial direction all OFIS recordings are convolved with their *n*-1 neighbor instrument responses and transformed back to the time domain where the misfit is evaluated for both hemispheres (although one could also analyze the misfit in the frequency domain). The ARC technique compares calculated waveforms that are more smoothed than any of the predicted individual OFIS recordings from the WLD or SAD methods.

**Resolution and Signal to Noise Ratio**

The above OFIS array methods rely on two types of phase velocity direction resolution: time separation and instrument response discrimination. Time separation is the property that is exploited in classical array processing, either in time or frequency space. Instrument response discrimination (spectral resolution) is a unique form of resolution enjoyed by any sensor that averages along a line. However, given the amplitude decay of the response function at higher frequencies, there is a balance between spectral resolution and SNR (Fig. 3). As the noise floor increases, the higher signal frequencies that are recorded by OFIS arms at oblique angles get buried in the noise. Alternatively, for signals that only have frequencies below 1 Hz, there is no spectral resolution for a 90-m OFIS. If the noise floor is above the water level used in the WLD technique, noise can be amplified, degrading the resolution by an amount dependent on the OFIS configuration. One must take care to pick the optimum value of the high cut frequency when using a bandpass filter to isolate the band of greatest spectral resolution (Fig. 3).

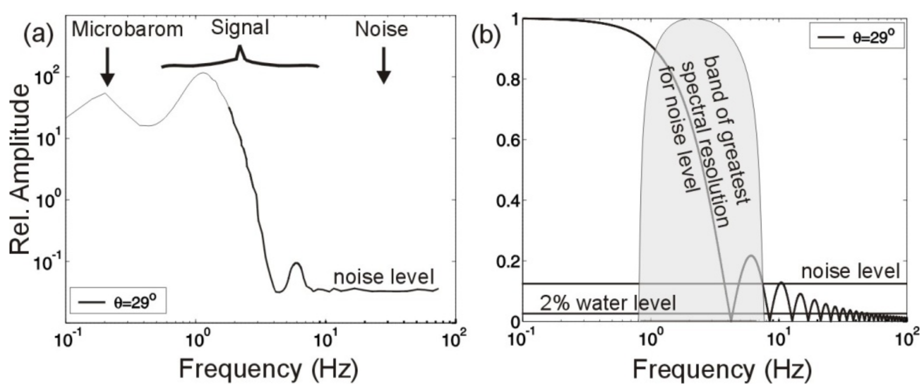



**Fig. 3. Cartoon of the infrasound band of greatest spectral resolution, and how it relates to the length of the OFIS arms, a heuristic noise level, and phase velocity direction.**

The SAD technique can be more stable for higher noise floors because it weighs the $i^{th}$ frequency of all OFIS spectra by the amplitude of the associated predicted instrument response function, resulting in little contribution in the deconvolved signal from energy below noise floors that are significantly lower than the peak of the signal spectrum. However, if the noise floor is too high on one of several OFIS arms, this noise will be mapped into the deconvolved signal because SAD is a least squares technique that can weigh the spectrum of an uncharacteristically noisy OFIS greatly, which can quickly degrade the back azimuth resolution since all OFIS comparisons are made using the noisy deconvolved signal spectrum.

The ARC method may also be more stable for higher noise floors, since there is no potential to amplify noise. However, this multi-filter technique can potentially reduce the signal strength recorded on all the OFIS (including ones aligned perfectly to record the signal) to the point where lower frequency noise begins to dominate the spectrum. For fair to poor SNR, one must take particular care to isolate the signal energy with the optimum low-cut frequency. The choice of high-cut frequency is not as sensitive, since most of the higher frequency noise energy is beat down by the method.

**Application to Real Data**

During the summer of 2005, we recorded many infrasound signals with varying SNR with a 3-120º OFIS collocated with an IMS infrasound array at Piñon Flat Observatory (PFO), in the southern California high desert. Comprised of eight elements fitted with rosette pipe filters, the array served as a reference with which to compare signal phase velocity directions. Infrasound at PFO originates from quarry mines, bombing ranges, sonic booms, rocket launches, and aircraft flying out of Los Angeles. Most signals observed by the OFIS were in the 2–10 Hz range, and were recorded by the high frequency (HF) subnetwork (aperture of ~130 m). A known timing problem with one of the data loggers limited our analysis to only three HF elements. To facilitate data processing, we limited our analyses of the OFIS data to the 2–5 Hz band for the WLD and SAD techniques. For the ARC technique, we had the same low-cut frequency, but chose the high cut based solely on inspection of the data. For the pipe array, we chose the optimum bandpass filter, which usually was 2–5 Hz. We show results for signals with elevation angles of 0-60º as determined by the pipe array. The speed of sound was determined by the temperature during the time of the recording.

Figure 4 shows the waveforms for the optimum parameters (BAZ, ELE) for the WLD, SAD, and ARC methods as applied to one of the PFO events. The unattenuated signal waveforms are estimated for each OFIS (blue) and subsequently averaged (top, light blue) using the WLD method. The SAD method also estimates the signal waveform (top, green). The 0.92 correlation indicates a good match. The WLD estimate has higher amplitudes presumably due to noise amplification. The observed (black) and predicted (WLD/red, SAD/green) OFIS recordings from the WLD and SAD methods correlate well, but the SAD predictions are consistently better with an average correlation of 0.98 (versus 0.93). The three array responses (purple) correlate very well with their average.

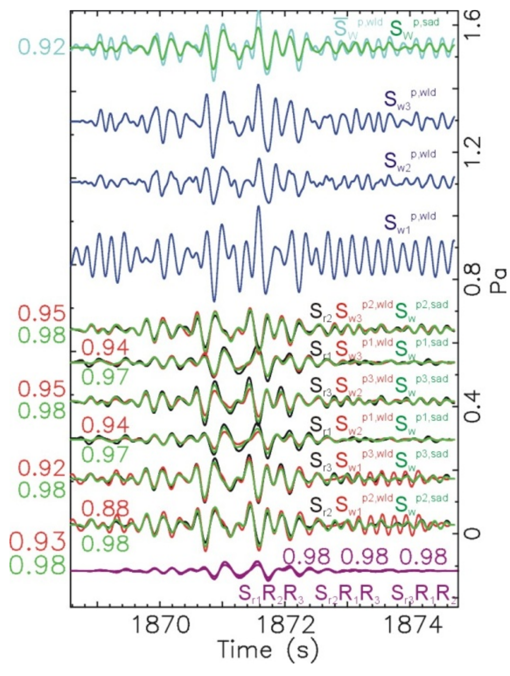
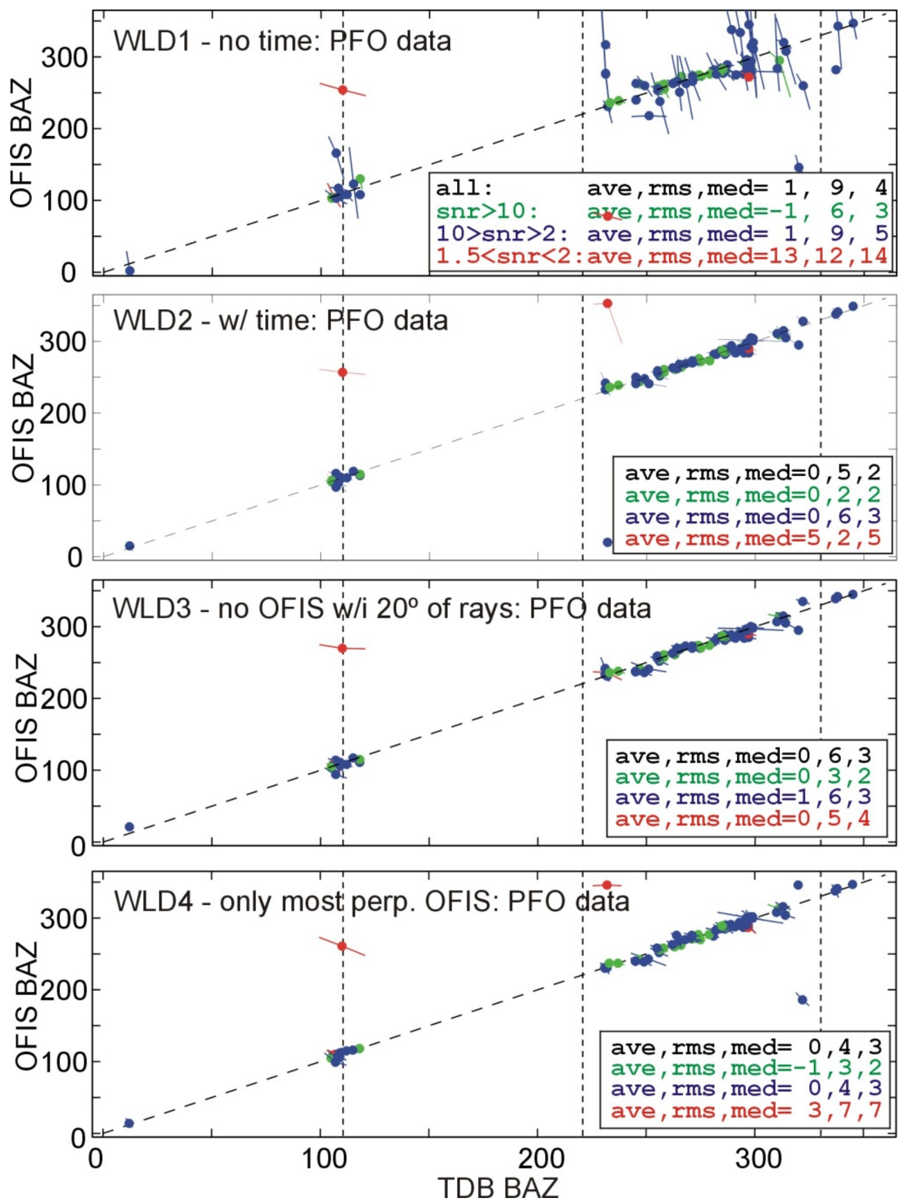



**Fig. 4. Analysis of PFO OFIS signal 2005/09/20 (263) 02:31:09 UTC originating from BAZ=287º, ELE=43º.**


WLD1 - no time: PFO data
all: ave,rms,med= 1, 9, 4
snr>10: ave,rms,med=-1, 6, 3
10>snr>2: ave,rms,med= 1, 9, 5
1.5<snr<2:ave,rms,med=13,12,14
WLD2 - w/ time: PFO data
ave,rms,med=0,5,2
ave,rms,med=0,2,2
ave,rms,med=0,6,3
ave,rms,med=5,2,5
WLD3 - no OFIS w/i 20º of rays: PFO data
ave,rms,med=0,6,3
ave,rms,med=0,3,2
ave,rms,med=1,6,3
ave,rms,med=0,5,4
WLD4 - only most perp. OFIS: PFO data
ave,rms,med= 0,4,3
ave,rms,med=-1,3,2
ave,rms,med= 0,4,3
ave,rms,med= 3,7,7
OFIS BAZ
TDB BAZ
0
100
200
300

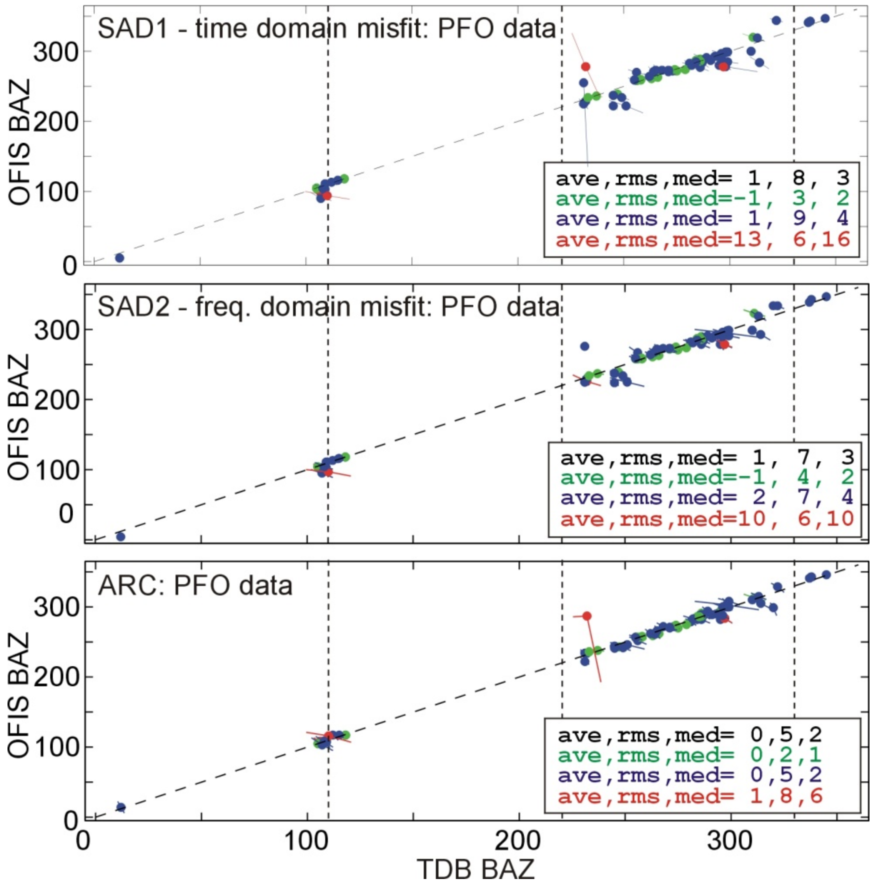



**Fig. 5. Comparison of real signal back azimuths (recorded by a 3-120º OFIS and collocated pipe array at PFO) using several OFIS methods and time domain beamforming for the pipe array. SNR is the average amplitude signal-to-noise ratio of the OFIS-recorded signal.**

The OFIS back azimuths from seven techniques are compared against those obtained with time-domain beamforming (TDB) using the pipe array (Fig. 5). The TDB uncertainty is obtained using the same technique as that for most of the OFIS methods, and is therefore directly comparable. The plotted error bars indicate the vector sum of the OFIS and TDB error bars, and should span the unity-slope dashed line. The vertical dashed lines indicate the azimuths of the OFIS arms, where one might expect to find difficulty for some OFIS methods for low SNR. The BAZ differences within +/-25º are used to estimate the average, RMS, and median absolute deviations.

The WLD1 results are one measure of the spectral resolution power for a 3-120º array with 90-m arms for signals in the 2-5 Hz band. Time separation is not used for these results ($R_p$ is set to 0, and for each trial ray, a cross-correlation is applied between the predicted and observed waveforms and the optimum lag is used). Only for excellent SNR does the technique gives fair results. One can also observe inaccuracy for signals associated with rays that are subparallel to an OFIS arm. Spectral resolution would be better if the ratio of the OFIS arm length to signal wavelength was greater, or if the *effective* angular separation of the OFIS arms (60º for 3-120º configuration) was smaller (e.g., a 5-72º or 5-36º configuration, both of which have a 36º effective separation).

The WLD2 technique includes time separation resolution. It performs better than the WLD1 technique at all SNR levels with an RMS and median absolute difference of 5º and 2º. Not using OFIS arms that are within 20º of the trial rays (WLD3) reduces the problems observed near the OFIS arm azimuths, but is in general not as accurate as WLD2. Only using the most perpendicular OFIS in the deconvolution step (WLD4) does not seem to perform much better than the WLD2 method. However, this can be explained by the reduction in the number of compared waveforms used throughout the misfit function (2 pairs in WLD4 versus 6 pairs in WLD2 per trial ray).

The SAD techniques (SAD1 is the time-domain misfit whereas SAD2 is the frequency-based misfit) perform about as well as the WLD2 and WLD4 techniques for excellent SNR. However, for lower SNR, they are superior to the WLD techniques (the outliers are generally corrected). Comparing the RMS and median values are not very meaningful for this SNR because the other methods did not generate many results within the +/- 25º range used to calculate the deviation statistics.

In general, the ARC technique appears to provide the most accurate results over the widest SNR range. All of the outliers (>25º) associated with the OFIS azimuths have been corrected, and ARC has the same overall deviation statistics as WLD2 with RMS and median absolute deviations of 5º and 2º, respectively. However, upon detailed comparison between the deviations in the excellent, good, and poor SNR ranges, ARC is superior to the WLD2. In fact, a difference of 20º for a single ARC value is what gives rise to the 5º overall RMS. Without that one value, the RMS reduces to 4º (lowest of all methods). None of these techniques show evidence for a bias (significant non-zero average deviation for all SNR for any method).

## CONCLUSIONS AND RECOMMENDATIONS

Our results suggest that SAD is the best method to remove the instrument response and recover the unattenuated infrasound signal. In addition, the ARC method yields estimated back azimuths that are the most similar to those obtained by classical array processing techniques like beamforming. However, most of the other techniques that use spectral and time separation resolution also perform fairly well, and also can lead to more precise estimates of back azimuth than a pipe array of comparable aperture and number of sensors.

The PFO phase velocity directions, determined by a three-OFIS array (3-120º) located on the surface with a 180-m aperture, are similar in accuracy and uncertainty to that provided by a collocated, three-element subnetwork of a certified IMS array with 18-m rosettes separated by roughly 300 m. An OFIS is more prone to instrument noise on the surface than when it is buried. A buried 90-m OFIS has a noise floor as much as 20 dB lower than the low-frequency rosette pipe array elements in the 1–10 Hz band (Zumberge et al., 2003). Based on our comparisons between different algorithms, and on synthetic data tests, we conclude that one attractive solution for determining phase velocity direction for all possible directions and frequencies down to 0.05 Hz is to have four OFIS elements in a triangular array with a ~1.5 km aperture (Fig. 6a). Each OFIS element would have two collocated 5–72º subarrays: one with 60 m arms and the other with 180 m arms. The two subarrays would be azimuthally offset by 36º. This would give adequate spectral and time resolution in the 0.5–12 Hz range *within each of the four elements* using the ARC technique. One obtains an even greater resolution when the 0.5–12 Hz results from each element are combined. Resolution for lower frequencies (0.05-0.5 Hz) would be obtained only by the time separation of the four triangular elements. The OFIS elements would be buried to insure that the noise floor would be significantly lower than that provided by rosette pipe arrays in wind speeds up to at least 3 m/s, and possibly 8 m/s based on recent observations.

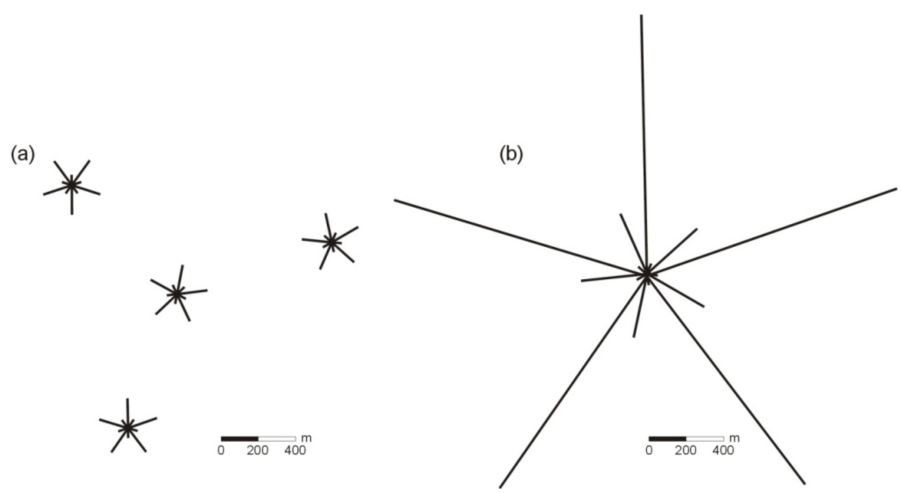



**Fig. 6. Possible OFIS configurations as an alternative way to measure infrasound signals in the presence of wind noise.**

Although the optical system for OFIS arms that are longer than 180 m has not been tested, another attractive solution for the same 0.05–12 Hz range would be to have just one OFIS rosette comprised of three 5–72º subarrays with different OFIS lengths: 1440 m, 360 m, and 60 m (Fig. 6b). This solution provides spatial averaging of the coherent signal over a much longer distance, which may provide better wind noise reduction than the first configuration. Both of these buried OFIS solutions only require a narrow trench of about a foot in depth, and disturb less surface area than a buried, rosette pipe array infrasound station. The OFIS configurations also have a lower profile because they do not have a surface expression other than the lines of gravel-filled trenches.

The ARC technique would be simple to implement on the second configuration because you could use this technique for all three 5–72º subarrays. For a broadband signal, one could combine the final misfit functions from the three 5–72º configurations to determine the phase velocity direction. The first configuration could also use the ARC method, and combine the misfits from all four triangular array elements, but only for the 0.5–12 Hz band. Analysis of the 0.05-0.5 Hz band would require using each of the 40 OFIS arms (or four elements if you stack the intra-element OFIS signals) with classical array processing software.

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